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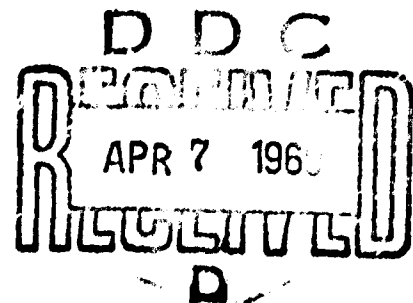
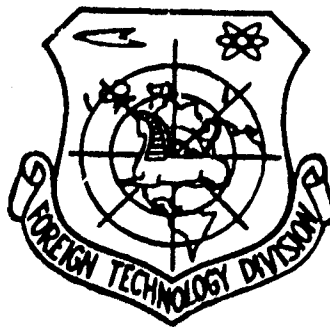
FOREIGN TECHNOLOGY DIVISION



THE BASIC PROPERTIES OF MATERIALS AND DESIGN WHICH
DETERMINE THE SERVICE LIFE OF NOZZLE BLADES

by

A. A. Rabinovich, V. G. Chubarov, et al.



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EDITED TRANSLATION

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Solid and hollow gas turbine nozzle blades made from cast and wrought heat-resistant alloys were tested for warping, thermal fatigue, and gas corrosion under laboratory and actual operating conditions. Solid blades were cast from the VZhL8 and VZh36L1 chromium-nickel-base alloys, the 4K66Ya chromium-cobalt-base alloy, the VZh36L4, ZhS6K, ZhS6KP, HS245, ZhS3DK, and K14N56LYa chromium-nickel-cobalt-base alloys, and the ANV300 cast alloy. Hollow blades were formed from 2-mm-thick sheets of the EI602, EP99, and EI867 nickel- and nickel-chromium-base alloys and welded along the trailing edge. In tests at 1173°K for up to 100 hr, the blades made from the EI867 alloy sustained at 3-5 mm warping after 50-60 hr; the corresponding times for the EP99 and EI602 alloys were 20-30 and 5-10 hr, respectively. The alloys with a higher resistance against warping also had a higher rupture strength. In gas corrosion and erosion tests at 1173°K, the EP99 wrought alloy, the ANV300 cast alloy, and the ZhS6K cast alloy modified with an addition of 20% Cr exhibited the highest resistance against gas erosion and corrosion. The thermal fatigue resistance of blades cast from the cast alloys investigated was found to depend either on the physical properties of the alloy (coefficient of expansion, heat conductivity), or on the mechanical properties (strength, ductility, impact toughness). Failure from thermal fatigue and stress-rupture tests (see Fig. 1) revealed no correlation between the alloy heat

resistance and thermal fatigue resistance, although both depended on the condition of intergranular boundaries. Resistance to thermal fatigue can be increased 10 times or more by improving the design of the blades. In the case of blades made from ZhS6K, ZhS6, and ANV300 alloys, a 2-4 mm increase in the radius of curvature of the leading edge resulted in a 150-200% increase in the thermal fatigue resistance. The thermal fatigue resistance of hollow blades and blades with a thinner profile was 4-6 times higher than that of the initial blades (solid cast blades with a leading edge having a curvature radius of 2 mm). Sectional blades consisting of two parts had no thermal fatigue cracks after more than 500 cycles of temperature changes from 273 to 1473°K. Orig. art. has: 3 figures and 2 tables.

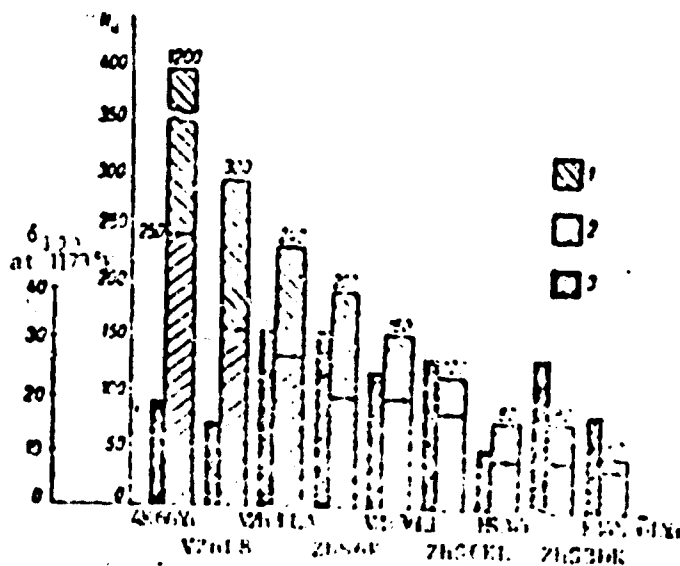


Fig 1. Thermal fatigue resistance of cast nozzle blades.

- 1 - Number of cycles before the appearance of surface cracks;
- 2 - Number of cycles before the appearance of through-cracks;
- 3 - rupture strength.

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REPRODUCIBLE**

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A. A. Rabinovich, V. G. Chubarov, et al.

The basic defects of nozzle blades which one meets with in the operation of gas-turbine installations are warping, cracks from heat fatigue, and damaging of the surface as a result of gas corrosion.

The purpose of this investigation is to bring out the causes of the breakdown of nozzle blades, evaluate the service capacity of the different materials and the designs, and mark out ways of improving the dependability of nozzle blades.

Tests were carried out on a special setup representing a section of a combustion chamber under conditions which were as close to actual operations as possible [3]. Subjected to test were hollow and monolithic nozzle blades of one of the series-manufactured products prepared from cast and shaped heat-resistant materials [2, 3].

For evaluation of the resistance of the alloys to warping there were tested hollow nozzle blades prepared from sheet materials EI602, EI99, and EI867 (of the thickness of 2 mm) welded on the outer edge. The tests were conducted in steady and varying temperature regimes imitating the conditions of starting, stopping and working under regular operating conditions.

After a hundred cycles of heat change there was observed an insignificant warping of the profile of the blades made of alloy

EI602 (of the order of 1 mm). On the blades of the alloy EP99 the same amount of warping was observed only after 400-500 cycles. After a thousand cycles of heat variation on the blades of the alloy EI602 the maximum warping amounted to 5-7 mm and on the blades of the alloy EP99-2-3 mm, whereas on the blades of the alloy EI867 no warping was noticed.

The test on the setup with a steady temperature regime at 1173°K showed warping of the order of 3-5 mm on the blades of the alloy EI602 after 5-10 hours, on the blades of the alloy EP99 after 20-30 hours, and on the blades of the alloy EI867 after 50-60 hours.

Tests on the engine fully confirmed the data obtained with the tests on the setup. After 10 hours of work in the rated system the percentage of nozzle blades showing warping of about 3 mm was distributed among the alloys in the following way: for the alloy EI602 100%, for the alloy EP99 50%, and for the alloy EI867 20% of the blades. The results presented show that the greatest resistance to warping both under conditions of steady and under conditions of a changing temperature field is possessed by the alloy EI867, next to it comes the alloy EP99, and the least resistance to warping is noted in the alloy EI602.

By comparing the data obtained on warping with duration strength for the investigated alloys it is possible to draw a conclusion about the correlation of these characteristics:

Brand of alloy.....	EI602	EP99	EI867
σ , dan/mm ² , at τ = 100 h and T = 1173°K.....	3	10	19
Number of blades with warping more than 3 mm,%	100	50	20

The dependence of the resistance to warping on heat resistance of the material obtained on hollow blades holds good also for cast monolithic blades. On one of the series-manufactured items as the material of the nozzle blades there was used an alloy of the brand LK4. With a continuing margin of reliability for the working of the part there was noted considerable warping of these blades, which led

to a change in the gas-dynamic characteristics of the nozzle apparatus and the engine as a whole. With the going over to the more heat-resistant alloy VZhL8 (limit of 100-hour strength at the temperature of 1073°K 34 dan/mm² against 15 dan/mm² for the alloy LK4) one was able to eliminate fully the warping of the blade and increase the margin of reliability of the working of the nozzle apparatus.

The tests for gas corrosion and erosion were conducted on blades prepared from casting alloys ZhS6K, modification of the alloy ZhS6K with increase in the content of chromium (up to 20%), ANV300, and the sheet ones EI867, and EP99.

The comparison tests on the setup of the cast blades of the alloy ZhS6K, modification of the alloy ZhS6K (with 20% of chromium), and ANV300 at the temperature of 1173°K, showed that the alloy ANV300 and the modification of the alloy ZhS6K possess a higher resistance to gas corrosion and erosion. After 100-hour tests on blades of the alloy ZhS6K there were observed centers of local damage to the surface of the depth of 0.5-1.0 mm. On the blades of the alloy ANV300 and the modification of the alloy ZhS6K similar defects were not observed.

The comparative test of the blades made of sheet materials EI867 and EP99 showed that the resistance to gas corrosion and erosion of the alloy EP99 was considerably higher than for the alloy EI867.

Among the items the nozzle blades of the alloys ZhS6K and EI867 after 150 hours have local damages on the surface to the depth of 1 mm, whereas the blades of the alloys ANV300 and EP99 do not have such damages. Similar effects, but in a lesser degree (up to 0.1-0.3 mm), on the blades of the alloy EP99 were observed only after 1000 hours and more of work. The high corrosion strength of the alloys EP99, and ANV300 and the modification of the alloy ZhS6K, as compared with the alloys EI867 and ZhS6K is explained by the higher content of chromium. It is known that nickel alloys with a content of chromium of 15-25% have a high resistance to oxidation as the

result of the formation of a protective film consisting of spinels with a predominance of oxide Cr_2O_3 [2].

Reference data on the heat resistance of materials determined in accordance with increase in weight are found to be in contradiction with the data obtained by us. This is explained on the one hand by the local character of the breakdown of the surface in the process of corrosion in the operation of an engine, and on the other hand by the formation of volatile oxides (of the type MoO) which diminish the increase in weight in the process of testing for heat resistance.

In the Table 1 there are shown reference data on the heat resistance of the alloys, determined in accordance with the increase in weight at the temperature of 1173°K , the average content of chromium, and also the results of 100-hour testing of the nozzle blade of these alloys on an engine. In practical operation of gas-turbine installations there are observed cases of the appearance of cracks on the nozzle blades of the turbines as a result of uneven heating (or cooling) of the thin edges and massive central part of the blades in the process of rapid and rather great change in the temperature of the gas. The inequality of the temperature field in the transverse section of the blades in a number of cases can be quite great. The respective temperature stresses and deformations with much repetition of their occurrence bring about heat-fatigue breakdown of the blades. In connection with this the characteristic curve of the heat resistance of the material in many cases determines the service capacity of nozzle blades, especially, in the case of a long-lasting margin of reliability of the working of the part.

Table 1.

Brand of alloy	Wt. increase, g/m ²	Content of Cr, %	Results of testing on an engine
ZhS6K	0.025	10.5-13.5	Unsatisfactory
ANV300	0.031	14-17	
EI867	0.021	8.5-10.5	
EP99	0.13	11-24	
			Satisfactory

*Using sheet samples, after G. Ye. Moskalenko.

As a result of the regular tests of the nozzle blades made of cast heat-resistant alloys on chrome-nickel (VZhL8, VZh36L1), chrome-cobalt (4K66Ya), and chrome-nickel-cobalt bases (VZh36L4, ZhS6K, ZhS6KP, HS245, ZhS3DK, K14N56LYa) under conditions approaching to the maximum of those of the working of the part, the alloys as to their heat resistance lined up in a definite series (Fig. 1) [5].

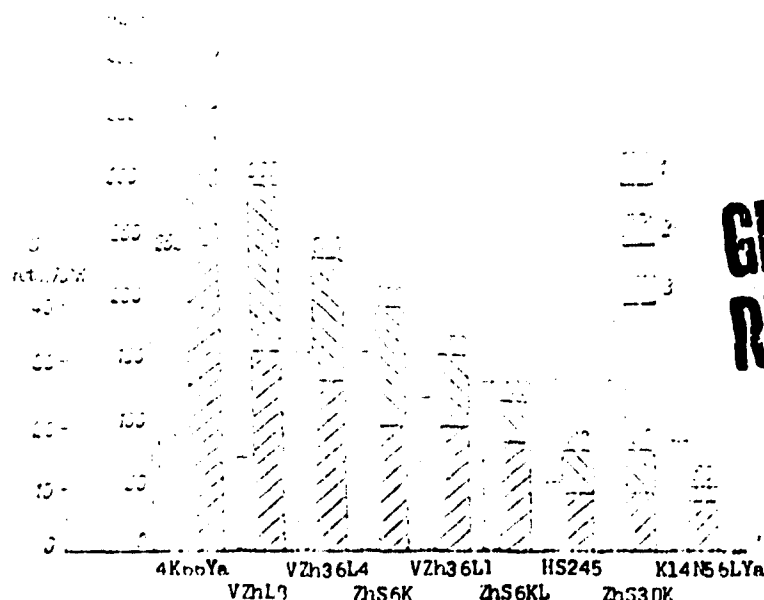


Fig. 1. Resistance to heat changes by blades made of cast alloys: 1, 2 — average number of cycles up to the appearance, respectively, of a continuous and surface crack, 3 — duration strength.

The cracks from heat fatigue in the case of tests of the blades of all the alloys were distributed selectively over the boundaries of the grain analogously to the breakdown of the nozzle blades from heat change on an engine.

It was established that the heat resistance of alloys is determined either by the physical properties of the alloys (coefficient of linear expansion, heat conductivity), or by the mechanical characteristics of the alloys (modulus of elasticity, strength and fluidity, characteristics of plasticity in short-period breakdown, and impact viscosity), and the breakdown from heat change occurs as a result of the formation of surface cracks and the development of one or several of them crosswise.

The distribution of the cracks from heat fatigue, preferably along the boundaries of the grain, points to the fact that the breakdown occurs at a temperature above the equicohesive, and the heat strength of the material depends on the state and property of the material close to the intergranular boundaries.

The kinetics of the process of breakdown is analogous. In the process of creep under the action of the concentration of stresses there is observed the formation of microscopic cracks and the development of them preferably along the boundaries of the grain. A correlation between the characteristics of the heat strength and the thermal stability is lacking (see Fig. 1). At the same time the characteristics of the heat strength and the thermal stability are interconnected since both depend on the state of the intergranular boundaries of the material, which is confirmed by the following experiment. Specimens of the alloy ZhS6K before the test for heat strength were subjected to thermocyclic action of 300, 500, and 1200 cycles. In view of the fact that the round form was favorable from the point of view of the extent of the thermal stresses arising even after 1200 cycles the specimens did not have visible cracks (the blades of the alloy ZhS6K had transverse cracks after 200 cycles).

In accordance with Fig. 2 the stability of the specimens after preliminary heat-cycle treatment diminishes; after 300 cycles by 35, after 500 cycles by 60, and after 1200 cycles by 80%. Such a lowering of the stability of the specimens is explained by the damaging of the intergranular boundaries of the material under the action of heat change, which apparently leads to a lowering of the relaxation capacity of the boundaries of the grains, which is determined by the intergranular plasticity of the material. One of the components of the general plastic deformation in the process of creep is the plastic deformation in accordance with the mechanism of the intergranular plasticity.

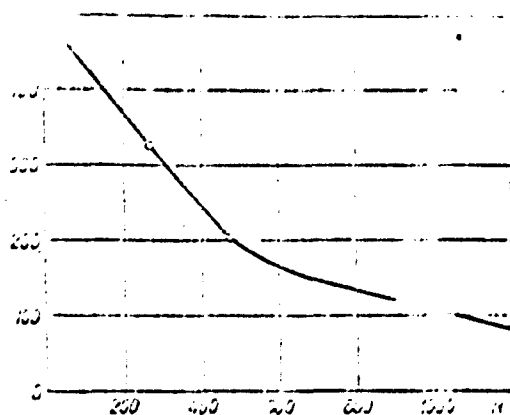


Fig. 2. Curve of the stability of specimens of the alloy ZhS6K in testing for duration strength at the temperature of 1223°K and stress of 12 dan/mm² after preliminary thermocyclic treatment.

It is possible to evaluate qualitatively the intergranular plasticity by comparing the plasticity of the alloys after lengthy tests at temperatures of embrittlement of the alloy, while with the increase in the duration of the test (i.e., with a lowering of the stresses) the share of the intergranular interplastic deformation in the general deformation of the specimen increases. The competence of such an evaluation of the intergranular plastic deformation is proved in the reports [6, 7, and others].

In view of the different level of the heat strength of the investigated alloys it would be, apparently, inaccurate to compare all the alloys as to the plasticity after the tests for duration strength. Comparison, however, of the duration plasticity of the alloys close with respect to heat strength is quite accurate. Of the investigated alloys close limits of the 100-hour duration strength is had by the alloys, 4K66Ya, VZhL8, K14N56LYa, VZh36L4, ZhS6K, VZh36L1, ZhS6KP, and ZhS3DK.

In the Table 2 there are presented data which we have on the level of plastic deformation after 100- and 500-hour tests for duration strength of the two groups of investigated alloys.

Table 2. Plasticity of cast alloys after tests for duration strength.

Brand of alloy	T, °K	Time of test, h	Plasticity, %	
			δ	ψ
4K66Ya	1073	100	10-13	15-20
VZhL8	1073	100	5-12	12-17
		500	3-7	7-9
K14N56LYa	1073	100	3-8	5-10
		500	1-3	2-3
VZh36L4	1173	100	6,7	12,1
	1248	100	7,5	22,1
ZhS6K	1173	500	2,7	3,1
	1248	500	2,4	2,6

As follows from the data of Table 2, between the duration plasticity and the thermal stability there exists some qualitative correlation. An alloy with great duration plasticity resists better the action of thermal cyclings.

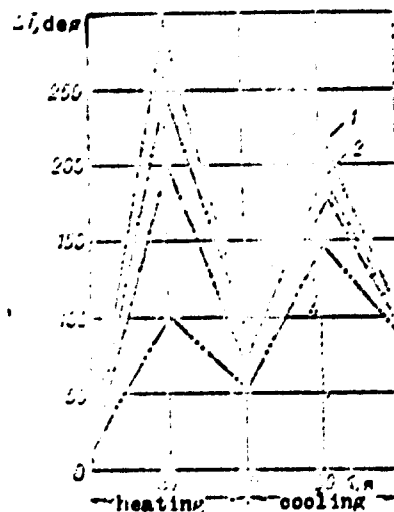
Unfortunately, we are not in possession of data on the plasticity after 1000-hour and longer duration tests for duration strength. In this case correlation, in our opinion, would appear more precise, since in the process of creep under weak stresses the mechanism of intergranular plasticity has a deciding significance. In accordance with the group of alloys VZh36L1, ZhS6KP, and ZhS3DK there is observed an analogous conformity to rule. A higher duration plasticity is had by the alloy VZh36L1. It also shows greater thermal stability.

The service capacity of the nozzle blades under conditions of thermal cyclings (alternating regimes) can be increased considerably with other conditions remaining equal by means of perfecting the design form of the blade [1].

The variation in the temperature field in the cross section of the blades can in a number of designs be very great, in connection with which the respective temperature stresses and deformations with much repetition of them results in thermal-fatigue breakdown of the blades.

On the setup there were carried out cyclic tests of four different design variants of a nozzle blade with a single profile with measurement of the temperature field in an average section of the blade in the process of one cycle. The tests showed that by change in the design it is possible to improve the thermal stability of the blades by a factor of 10 and more. The most rapid heating and cooling of the input and output edges as compared with the central part (on the solid blade) and the more equal heating and cooling on the other blades (hollow, compound, solid blade with tapered profile) bring about greater or lesser thermal stress, and as a result, cracks at the edges.

In Fig. 3 there are presented the maximal jumps in the temperature over the profile of the different design forms of the blades in the course of a cycle of heat change. The cycle is characterized by the change in the temperature of the gas from 293 to 1473°K.



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Fig. 3. Graph of the maximal jumps in the temperature over the profile of the different forms of the blades in the course of a cycle of heat change: 1 - solid blade, 2 - hollow blade, 3 - blade with tapered profile, 4 - compound blade.

An increase in the radius of the rounding of the input edge (of from 2 to 4 mm) improved the thermal stability of the blades made of the cast alloys ZhS6K, ZhS6, ANV300, and others by a factor of 1.5 up to 2. The thermal stability of the hollow blades and the blades with a tapered profile was 4 to 6 times better than that of the original blades (solid cast blade with radius of edge of 2 mm). The compound blades, consisting of two parts after a great number of cycles (for example, 500) had no cracks.

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